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Greening the power generation sector: Understanding the role of uncertainty

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ABSTRACT

The transition to low-carbon technologies is essential to meet international climate change agreements. While market dynamics are contributing to make technologies increasingly affordable, experience has shown that other factors as well play a role in investment decisions. Uncertainty is one of them. Focusing on the power generation sector, this paper reviews the most recent literature on the subject, under the specific conditions that at least one adoption driver is uncertain and that a technology and/or environmental policy is in place. To understand how uncertainty affects adoption decisions, the survey considers economic parameters (e.g., investment costs or electricity prices) first and then focuses on the role of policy. While the deterring effect of uncertainty over investments is largely confirmed, several mitigating and underexplored issues are also identified, such as the role of heterogeneous investors' characteristics or the welfare implications of different policy designs. Moreover, by explicitly considering policy uncertainty, this survey provides a clearer understanding of the effects of a lack of government commitment on the adoption of environmentally friendly technologies in the energy sector. Related challenges for policymakers and investors are carefully delineated, together with directions for further research.

1. Introduction

The transition to a low-carbon energy system is one of the great societal challenges of the coming years. Electricity and heat production accounts for 25% of total greenhouse gases emissions, and reducing this contribution is fundamental to meet the Paris Agreement goals [1]. In this respect, the electricity sector has been experiencing a transformation for quite some time, and the large majority of investments in power generation are currently forecasted to involve renewable energy sources (over 70% in the period 2017–2040, [2]). Although market dynamics, with the decreasing costs for wind and solar installations, represent an important driver, they are still not expected to deliver by themselves the level of investment necessary to meet the 2 °C temperature target [2]. Policy interventions will continue playing a key role in reconciling climate change mitigation and sustainable economic growth.

Yet, geographical differences remain large. In the European Union, where the share of electricity produced by Renewable Energy Sources (RES) has already reached 29% in 2015 and is expected to grow up to 50% in 2030, policies are evolving at a fast pace. The latest package of measures launched by the European Commission in late 2016 comprehensively addresses the transformation of power systems, by focusing on market rules that will favor investments in renewables and in other fast-advancing technologies (e.g., storage), as well as on consumer empowerment. Indeed, the Commission places active consumers at the center of the policy agenda, as new technologies enable them (individually or in aggregation) to produce their own electricity and to respond to market signals, thus facilitating the integration of intermittent, renewable generation [3]. In the US, despite the initiatives to address climate change are rather significant at the state level, the adoption of a more incisive federal policy continues to be unlikely, at least in the short term [4]. China is expected to remain a large coal consumer for the next two decades, and achieving universal access to modern and sustainable energy in emerging economies is proving rather challenging [2,5].

Against this background, numerous studies have addressed the question of the adoption of environmentally beneficial technologies, that is, technologies capable to reduce negative environmental externalities (not only in the energy sector). These contributions mainly confirm the findings of the broader literature on technology diffusion: relevant drivers include investment costs and revenues, the flow of information, as well as firms' or individual investors' characteristics.

Abbreviations: CCGT, Combine Cycle Gas Turbine; CCS, Carbon Capture and Storage; CDM, Clean Development Mechanism; ETS, Emission Trading Scheme; FIP, Feed-In Premium; FIT, Feed-In Tariff; IGCC, Integrated Gasification Combined Cycle; MILP, Mixed Integer Linear Programming; PTC, Production Tax Credit; PV, Photovoltaic; RES, Renewable Energy Source; RO, Real Options; RPS, Renewable Portfolio Standard; VPP, Virtual Power Plant

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There are, moreover, two distinctive factors that affect the adoption decision in less carbon intensive technologies specifically: attitude and knowledge about the environment and policy instruments [6].

The main contribution of this paper is to address one missing piece in the above description. Experience has shown that in the adoption of a green technology, as in any investment decision, uncertainty about future returns plays a crucial role in determining the timing and the size of the investment [7]. In presence of irreversibilities (such as sunk costs), uncertainty over any of the factors affecting the profitability of an investment has, most of the times, the effect of delaying it. Yet, investors' attributes, the pace of technological change or policy design features have the ability to mitigate or worsen this result. Hence, taken collectively, the way firms and individuals respond to the challenges posed by uncertainty will contribute to defining the ability to meet international climate change agreements as well as local environmental targets. For this reason, uncertainty is the common denominator of the contributions selected for this work, and the understanding of its effects on the adoption of less carbon intensive technologies is the main purpose of this survey.

The focus is on the power generation sector, as a main global source of energy-related CO_2 emissions. The main question in this domain regards the profitability of a new technology, not only per se but also with respect to that of more traditional ones. Differently, analyses of electricity production costs are less relevant [8]. Accordingly, the studies included in this review are designed either to compare the profitability of two or more technological choices that entail different levels of emissions, or to assess the profitability of an investment in a new, cleaner technology (renewable or not) for power generation.

Moreover, all studies assume the presence of government intervention, either through an environmental policy (e.g., carbon policy) or through a technology one (e.g., renewable energy policy). This choice is justified not only by the role of policy as a driver of adoption, but also because, looking forward, government support for generation technologies is still expected to change, as policy makers strive to redesign market rules and create a level-playing field for all technologies.

A few surveys analyzing the relationship between uncertainty and investments in energy systems already exist but, in most cases, they are methodologically oriented. Soroudi and Amraee [9] and Aien et al. [10] provide an overview of the methodologies that can be used to model operational and planning problems under uncertainty. Similarly, the reviews by Fernandes et al. [11], Martínez Ceseña et al. [12], and Schachter and Mancarella [13] have a strong methodological characterization and only analyze real options applications.

The present work is more comprehensive than these surveys in terms of empirical approaches and, distinctively, also strongly oriented towards results and policy implications rather than methodologies. Specifically, the review is conducted along two lines: uncertainty over economic parameters, such as investment costs or electricity prices, is considered first, together with its effect on the adoption decision; then, the role of policy is addressed. By explicitly considering contributions where the policy regime is itself uncertain, this work provides, to the best of authors' knowledge, a first summary of the effects of policy uncertainty on the adoption of less-carbon intensive technologies for power generation.

The remainder of the paper is organized as follows. A general conceptual framework motivating the analysis is presented in Section 2, while Section 3 illustrates the inclusion criteria for the selected studies. Relevant outcomes that derive from uncertainties in revenues, input prices, and investment costs are discussed in Section 4. The results regarding the effect of policy and, in particular, of an uncertain policy are the focus of Section 5. Both sections also include policy recommendations and/or directions for further research. Section 6 concludes.

2. Conceptual framework

A fundamental step in understanding the effect of uncertainty on the diffusion of green technologies in power generation is to identify its sources. Soroudi and Amraee [9] make a distinction between technical and economic uncertainties, to discern between factors under control of the decision maker (or internal to the project) and purely exogenous ones. Because adopting a new technology is a planning decision (not a project design one), the scope of this review mainly covers uncertainties of economical/external nature (e.g., input prices) and relatively less technical/internal ones (e.g., wind availability).

Accordingly, among the economic/external factors that might create uncertainties over the profitability of a green investment in power generation, the present work considers, first of all, the elements that are common to any technological investment, namely *revenue-* and *cost-related* factors. The former are represented by electricity price and demand, while the latter comprise *investment costs* and variable costs in the form of *input prices* (fuel and CO_2 prices). The effect of a few *technical factors*, such as the rate of technical change (linked to investment costs) or renewable resources' availability (affecting the revenue stream) is consistently included in the previous categories.

The relative magnitude of revenues and costs is clearly crucial in the decision to invest [6]. Nevertheless, the unpredictability of one or more of these factors makes the optimal investment response more complex. Moreover, there might be potential behavioral biases in the investment decision. In this regard, this survey summarizes the findings of the literature on the relationship between revenue- and/or costs-related uncertainty and investment timing (and size), and discusses the related implications for the current technological transition. The survey also highlights the role of other potentially relevant factors, such as investors' characteristics and capabilities, and draws attention to under-researched areas.

Then, because of its importance for less carbon-intensive investments, particular attention is directed at the role of the *policy regime*, which can take the form of carbon and/or renewable policies. In fact, the presence of such policies is not always reducing uncertainty in the power sector. On the contrary, given the frequent policy revisions, investors are likely to be exposed to a further element of (hardly removable) uncertainty in their adoption decision.

Allan et al. [6] summarize the evidence concerning the effect of different, albeit stable, policy instruments on investors' technology choices in the adoption of green technologies in any sector. The present review adds to this work in two ways: by looking at the effect of a stable policy framework on the adoption of green technologies in the power sector specifically; and by explicitly addressing the issue of policy uncertainty. In this regard, it is essential to note that policy-related and other revenue- or cost-related uncertainties tend to overlap in many contributions. Specifically, some authors identify policy uncertainty with CO_2 price volatility or with green certificates' price variance. This review departs from this definition by introducing a clear distinction between the uncertainty generated by the kind of policy in place and the uncertainty on the policy itself. As for the former, the uncertainty derives, for instance, from a green certificates system making the unit revenue from the sale of renewable power variable (such an uncertainty is included, in this survey, in the "electricity price" or revenue class), or from a variable CO_2 price generating uncertain input prices for conventional power plants (included in the "CO_2 price" or input price uncertainty class). Hence, the category "policy uncertainty" only includes contributions where the uncertainty is on the policy itself, that is, on its introduction/termination, as well as on changes in its implementation details. This approach leads to a clear summary of the evidence regarding the relationship between policy uncertainty and adoption of less-carbon intensive technologies, as well as to the identification of issues that deserve further research.

3. Selection of the studies included in the review

The articles included in this survey were retrieved through electronic searches in bibliographic databases, as well as backward and

forward citation tracking in published and unpublished work. The article selection criteria were established along the definitions of participants, interventions, comparison groups and outcomes, following the standards of systematic reviews.

As for participants, all the articles design the problem of investment from the point of view of a single investor of different type (a professional or not professional individual, or a government body), in an IEA (International Energy Agency) member country, plus China. The interventions are environmental and/or technology (renewable energy) policies aimed at promoting the adoption of a green technology for power generation, when the future overall profitability of such an investment is uncertain – at least one of the factors listed in Section 2 is uncertain. Available comparisons regard the impact of a few variables and/or modeling assumptions. These include, for instance, the investor's characteristics, the rate of technological change, the presence of overlapping policies, and so on. For all contributions included in the analysis, the outcome of interest is the relationship between the uncertainty and the timing of the investment decision and/or, less frequently, the size of the investment.

The search resulted in the selection of 61 scientific articles published over the period 2003–2016.[1] As shown in Fig. 3.1, the studies were mainly published in the last two years (18 articles). Although the selection includes a variety of methodological approaches, most studies follow the seminal work by Dixit and Pindyck [14] and consider a real options perspective. In this setting, the decision to adopt a new technology by a single investor is seen as an option that can be exercised immediately or later in time, depending on the value of the option itself. Assuming investment irreversibility (investing now generates an opportunity cost), such value crucially depends on the degree of uncertainty. Specifically, uncertainty increases the value of keeping the option open, that is, of delaying the investment timing. This line of reasoning well characterizes the context of interest and explains the predominance of real options studies in this review. Notably, most of the articles employing a different methodological approach are still of quantitative nature, such as stochastic optimizations and/or simulations, as well as panel data analyses and theoretical models. Only three articles are based on surveys or case studies.

From a chronological perspective, it emerges that at the beginning of the observation period researchers were mostly interested in the uncertainties over fuel and electricity prices. As illustrated in Appendix A, studies started to include uncertainties on CO_2 prices mostly from 2007, while policy uncertainty received increasing attention after 2009. As for the technologies, Appendix B shows that there has been a considerable variety over the entire observation period, with studies dealing with both fossil fuel and renewable technologies. In the last years only, the focus has been mainly on renewable technologies, like wind and solar photovoltaic (PV). This likely reflects the fact that, by looking at the technology mix, the electricity sectors of the countries considered are often very different, in terms of geographical morphology, availability of natural resources, and sector regulation. This also explains why the studies included in this review generally consider a single, geographically specific investment environment.

The complete list of the selected contributions is provided in Appendix C, Table C.1 (uncertainty on factors other than policy) and Table C.2 (uncertainty on the policy), together with an indication of the relevant technologies, countries, policy regimes, as well as methodological approaches and outcomes for each article.

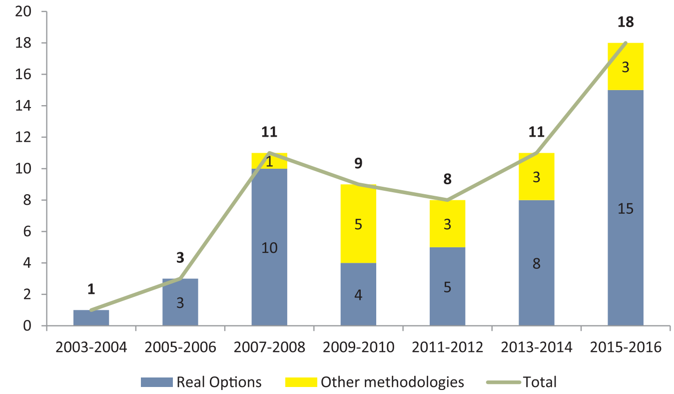

Fig. 3.1. Number of surveyed articles, 2003–2016 (biannual data).

4. Revenue- and cost-related uncertainties

All studies regarding less carbon-intensive investments in the power generation sector provide one fundamental insight: revenue- and cost-related uncertainties generate a value for waiting before taking an (irreversible) investment decision. Such a result is robust to the methodological approach (i.e., is not restricted to the real option realm), as well as to different sources of uncertainty. As an example, Abadie and Chamorro [15] describe the delaying effect of electricity prices (revenue) and CO_2 prices (input prices) uncertainty on investments in Carbon Capture and Storage (CCS) devices, where deferral increases with both variables' volatility. As highlighted by Reuter et al. [16], this holds true when the (revenue) uncertainty is over the availability of a renewable resource - wind in this case. While both studies take a real options approach, other methodologies lead to similar results. For example, Hu and Hobbs [17] employ a two-stage stochastic programming model and find that uncertainties over future demand growth and natural gas prices can lead to under-investment and make coal technologies more attractive.

In light of this overwhelming evidence, there seem to be two directions for inquiry. A frequently explored question regards the relative role of different sources of uncertainty. The issue has been considered in several studies, but without clear results. For example, through Monte Carlo simulations applied to CCS retrofitting technologies, Di Lorenzo et al. [18] find that investment costs and input-fuel prices uncertainty are the main factors affecting the investment decision. Instead, in the real options realm, Himpler and Madlener [19] find that revenue uncertainty is the main barrier to onshore wind repowering investments, not investment costs.[2] In the context of residential PV systems, Drury et al. [20] show that uncertainty on technological progress prevails over solar availability uncertainty, but revenue uncertainty also plays a major role when retail prices are high and variable. Overall, which is the most relevant source of uncertainty to investors depends on the technology considered, as well as on the context. Thus, the literature findings cannot be generalized.

A second, more prolific line of research questions whether the effect of uncertainty on investments can be ambiguous – as assumed in the more general option-based model of irreversible investment under uncertainty [21]. In fact, this survey identifies three main enablers of such ambiguity: the investors' characteristics (the most interesting one), the planning horizon, and the rate of technical change. A few contributions addressing the problem of the optimal investment size also provide interesting insights. A summary of the findings for each aspect is provided below.

[1] Originally, the start of the observation period was 1999, that is, immediately after the Kyoto Protocol was signed, and when the liberalization wave in the electricity sector approximately started in many countries. However, the few articles published in the period 1999–2002, while focused on green technologies, were not dealing with any policy issue, and thus were excluded from the review.

[2] Himpler and Madlener [19] do not consider explicitly the source of revenue uncertainty (electricity price vs. subsidy). In this respect, Yang et al. [59], by computing the internal rate of return of onshore wind investments, find that price uncertainty is less relevant as compared to subsidy uncertainty.

4.1. Investor characteristics

Traditionally, the power generation sector has been characterized by a relative homogeneity of investors, being large energy companies, utilities, or social planners the main actors. However, with the advent of distributed generation, more attention has been recently paid to investors' heterogeneity (e.g., utilities vs. households). Moreover, in light of this technological evolution (but not only), some standard assumptions over investors' attributes (e.g., perfect rationality, risk neutrality, etc.) have been questioned. Although this survey includes only a few studies dealing with investors' characteristics, they still highlight several relevant issues.[3]

A first aspect relates to risk aversion. Fan et al. [22] build a two-stage partial equilibrium model to analyze investment decisions of two firms, which operate in a competitive setting and can only adopt one technology each (coal and gas, respectively). Under three different policy models (namely cap-and-trade with allowances' auction, cap-and-trade with grandfathering, and carbon tax), the analytical results show that, while risk-neutral firms make the same capacity choices independently of how allowances are assigned, risk-averse firms are particularly sensitive to the specific allocation scheme, because of the differences in the corresponding economic rent. More specifically, as shown in the computational application, "when all allowances are auctioned, risk-averse firms build more (relatively clean) gas capacity and less (relatively dirty) coal capacity than risk-neutral firms." The reverse occurs under grandfathering. This is because an allowance auction is perceived as a worse scenario compared to grandfathering: risk-averse firms assign a higher weight to such scenario, with consequences on the capacity choice.[4] Along the same line, but employing two-stage stochastic linear programming, Cristóbal et al. [23] consider the case of coal plants' retrofitting to highlight the tradeoff between expected profit and risk metric of such an investment. In this context, which assumes CO_2 price uncertainty, profit maximization would call for a delay in the CCS investment, while risk minimization would require its anticipation. In a real options framework, Kettunen et al. [24] find that, independently of the technology considered (coal vs. gas), risk-averse investors adopt a CCS device always later than risk-neutral ones, because they have a higher preference for waiting for the uncertainty to resolve.

A second aspect relates to the presence of multiple or heterogeneous investors in the project, as for example in a power purchase agreement. In this respect, Barradale [25] highlights the important role of independent power producers in developing and owing wind plants, together with tax investors (i.e., investors not willing to take on high risk, but attracted by the deriving tax credits) for financing. Through a dynamic long-term capacity model, Ritzenhofen et al. [26] compare investment decisions made by homogeneous investors vs. heterogeneous ones (i.e., applying different discount rates in their investment evaluations). The study finds that the latter tend to invest in multiple technologies, resulting in a more heterogeneous generation mix.

A third aspect regards the size of the investor. For instance, Jensen and Meibon [27] analyze the decision to invest in wind technologies of two different subjects: an investor new to the liberalized electricity market and an investor already detaining a portfolio of power plants. As for the latter, the investment decision strongly depends on its effect on the existing portfolio. The new plant might change the income portfolio in such a way that investment costs are not covered at the beginning, so the investor will be inclined to postpone it.[5] Along the same line, Linnerud et al. [28] examine the Norwegian hydropower sector and find that while professional investors (e.g., utilities) follow a real options approach to choose the investment timing, nonprofessional ones (e.g., farmers) rather follow simpler Net Present Value rules.

Given the increasing diversity regarding actors in the power sector, as well as the higher complexity and variety of their interactions (consider, for example, energy communities), the ability to predict heterogeneous investors' behavior becomes increasingly important to understand the relevant determinants of the energy transition and to design effective policy instruments. Furthermore, the assumption of bounded rationality and, more generally, the introduction of insights from behavioral economics have the potential to broaden the understanding of small or not professional investors' choices, an extremely relevant issue in the evolution of the power sector. To give an example, Klein and Deissenroth [30] show that the final consumers' decision to invest in residential solar systems under a feed-in tariff regime can be interpreted in light of behavioral biases linked to profitability changes compared to the status quo. These critical issues need to be further addressed by future research.

4.2. Planning horizon

The choice of the planning horizon length can have an impact on the extent to which two technologies are "competing" and, as a consequence, on green technologies diffusion. All the examples in the selected literature (for different types of technologies) point in the same direction: the longer the planning horizon, the earlier the adoption of a cleaner (implicitly, more expensive) technology.

The role of the planning horizon is discussed, for example, by Patiño-Echeverri et al. [31]. In this work, the owner of a coal power plant opts for replacing the old plant with a new, less emitting one rather than retrofitting it with a CCS device when the planning horizon is relatively long.[6] This is because the higher efficiency will be exploited for more years. By considering different residual lifetimes for conventional coal power plants, Zhang et al. [32] find an analogous result: the longer the residual life, the lower the critical carbon price that triggers immediate CCS adoption. Hieronymi and Schuller [33] show that, between a gas and a wind plant, under uncertain permit prices and different policy scenarios, a single investor will more likely invest in the first one, which is relatively less costly. Nonetheless, if the permit price development is taken into account over a longer period of time, the two technologies become more similar in terms of cost competitiveness. Finally, in the context of renewable technologies, Welling [34] shows that, the longer the plant lifetime (due to, for example, product innovation), the higher the probability of adoption.

Overall, the literature suggests that, in order to reach environmental targets, investors' planning horizon should be as close as possible to the one considered by a social planner concerned about future climate. In other words, it would be important to identify the factors that might induce investors to internalize social environmental costs. For example, more research aimed to understand how, besides mandatory policy compliance, investors update their beliefs on the need to address climate change problems would help in this respect.

[3] An explanation for this lack of studies might be the presence of a tradeoff which Gardner and Rogers [76] shed light on, that is, the one between how sophisticated is uncertainty modeling and how detailed is the modeling of the whole system under study.

[4] In a real options context, results' sensitiveness to the degree of investor's risk aversion is also found by Fuss et al. [60].

[5] Some other studies - not included in the survey because lacking the selection criteria - also highlight how the effect of uncertainty might also depend on the size of the investor.

(*footnote continued*)
For example, Keppo and Lu [77] show that, in absence of competition, a large producer whose decisions affect the electricity price might decide to postpone further the investment as compared as to a small one facing the same uncertainties. Moreover, Jouvet et al. [78] find that uncertainty over the degree of future competition might hamper investments.

[6] Other influencing factors are introduction and level of the CO_2 price, as well as emissions allowance prices for other pollutants. The result is stronger in presence of high CO_2 prices, which constitute a cost source for the plant owner.

4.3. Technological change

The maturity of a technology plays an important role in the adoption decision. In an early phase, it might take time for a new technology to be adopted due to, for example, high investment costs and/or lack of knowledge about the technology itself. Similarly, expectations of a decrease in investment costs thanks to technological progress might again lead to a delay in adoption. These two aspects are particularly relevant for environmentally-friendly technologies for power generation.

The first one is discussed in a number of studies in relation to CCS. Zhou et al. [35], Zhang et al. [32], and Wang and Du [36] point out that, together with the implemented carbon trading scheme, the current stage of CCS technological development (which, in turn, affects the uncertain investment costs) does not incentivize immediate adoption. This result seems to be confirmed for other technologies as well. Wang et al. [37], by introducing an uncertain parameter for technological improvements directly affecting investment costs, find a similar outcome in the context of biomass power production. Torani et al. [38] study the factors affecting the adoption of solar PV technologies in the residential and commercial sector. Under uncertain electricity prices and cost of solar PV, the authors identify R&D support and technological maturity as crucial determinants of adoption, while direct subsidies and taxes would play a minor role.

As for the second aspect, several studies point out the importance of the assumptions about the rate of technological change. Considering offshore wind power, Fuss and Szolgayova [39] show that prospective technological progress might delay the adoption. If such technological progress is also uncertain, the value of waiting increases even more. Notably, for more mature technologies like onshore wind, and specifically in the case of repowering, Himpler and Madlener [19] highlight that technological change might be less important. The authors assume uncertain investment costs because, in this context, it is not clear whether learning effects or loss in salvage value will prevail. Finally, always in the case of offshore wind power, Schwanitz and Wierling [40] argue that current predictions on decreases in future investment cost might be overly optimistic, and that negative learning effects might be expected instead, because of an increased design complexity. In other words, as uncertainty on technological progress remains high, policy incentives for building offshore wind parks might fail in reducing investment costs. Government interventions might be more effectively directed at optimizing the efficiency of the technology itself. In this respect, the work by Zhang et al. [41] seems to suggest a similar conclusion: reducing the costs of PV systems in China should be a priority, higher than reducing subsidies (which might expose investors to the risk of losses if inappropriately computed). To show this, the authors assume the presence of both learning-by-doing and learning-by-searching (from R&D expenses). However, the resulting two-factor learning rate is assumed to be constant. An interesting extension might entail a variable rate.

Overall, the availability of accurate predictions regarding technological change emerges as critical in modeling green technology adoption under uncertainty. As such, the study of factors affecting technological progress clearly deserves further exploration. It is worth noting that the interaction between uncertainty on technological progress and policy decisions regarding R&D spending has led to extensive and ongoing research that is, however, outside the scope of the present survey. For a survey of this stream of literature, the reader is referred to Anadón et al. [42].

4.4. Level of investment

Carruth et al. [7] highlight that real options studies focus on the factors that may affect the threshold at which an investment should occur, but not on its level. Indeed, this is true for most of the articles reviewed here, which take the level of investment as fixed (or do not mention it).[7] The few —all real options— studies that tackle this issue explicitly concentrate on the idea that, especially in the case of RES technologies, the capacity choice might reflect the possibility of modular, thus more flexible, investments [43].

Welling [34] analyzes investments characterized by flexibility in the choice of capacity. With the aim to identify factors hampering renewable technologies diffusion in Germany, the author finds that feed-in tariffs lead to larger installed capacities for a single PV system than a feed-in premium scheme. More generally, the type of scheme seems to count more than the amount of the support in the decision regarding the size of the investments.[8]

In the evaluation of sequential investments (first in a virtual power plant, then in a renewable plant), Garnier and Madlener [44] employ compound real options analysis to also consider the choice of the level of investment. The authors show that, under high volatility of market prices, subsidized technologies (e.g., wind) experience higher investment levels than non-subsidized ones, likely because of the presence of a lock-in effect. Interestingly, this work accounts for revenues coming from both the electricity and the balancing markets. While the presence of multiple remunerations is not new in the literature (e.g., under a feed-in premium system the generator receives the electricity price plus a fixed subsidy per produced unit), the fact that renewable sources might provide balancing services is an interesting insight, which has received considerable attention in power system studies (for instance, Morales et al. [45]), but has not appeared in the diffusion literature yet.

Overall, the literature seems to suggest that what determines the level of investment in a green technology is mainly related to the features of the support policy. Symmetrically, the size of an investment might be relevant to design supporting policies tailored to the type of investors (large utility vs. final consumer). Future lines of research should consider other aspects as well, such as the opportunities offered by changes in electricity market regulation (e.g., aggregation of small generators in virtual power plants) and the additional revenue streams deriving from changes in market design (e.g., provision of ancillary services by renewable/small power plants to the system operator). Finally, with the increase in RES penetration, more studies accounting for the effect of a high share of RES capacity on the level of electricity prices will be certainly needed.

5. Policy and policy uncertainty

By search design, all surveyed articles assume the presence of one or more policy provisions. Broadly speaking, such policies can be divided into two categories: environmental policies (e.g., carbon policies) and technology policies (e.g., RES support schemes). Being the overall objective of this section to provide an overview of the effect of policy on the adoption of green technologies for power generation, debate and findings holding under a stable policy environment are summarized in Section 5.1. The effect of policy uncertainty is considered in Section 5.2.

5.1. A stable policy

In the selected contributions, environmental policies are typically modeled as a carbon tax or, more often, as an emission quota system (such as the EU Emission Trading System) with a related market for

[7] Considering also the level of investment entails a higher degree of complexity in modeling. For example, in the real options approach, this implies the presence of multiple, compound options. The work by Fuss et al. [60] represent an attempt to overcome this problem. Specifically, the authors employ a combination of two methodologies (namely, real options and conditional value-at-risk framework) to assess green technology adoption decisions, as well as technology portfolios under different socio-economic scenarios. From the portfolio analysis, it emerges that the level of investment in the renewable technologies depends on both the socio-economic and the emission target scenarios: for example, biomass installed capacity is high in most cases, while wind capacity enters the optimal portfolio only when biomass prices are high.

[8] Nonetheless, the subsidy level still drives the capacity installed at the country level.

carbon allowances. Under both approaches, the level of CO_2 prices (besides its volatility) often emerges as a crucial determinant of the willingness to invest in a green technology – being a cost for "dirty" technology owners, a high CO_2 price would accelerate the timing of adoption of a "cleaner" technology. In this regard, however, the reviewed literature mostly points to the difficulty of an environmental policy alone to induce either retrofitting of conventional power plants or switch to RES.

One of the earlier studies finds that the price of pollution permits under the US Clean Air Act has not been sufficiently high to justify scrubber investments [46]. Along the same line, Abadie and Chamorro [15] show that the observed levels of the CO_2 price have been too low to make investments in CCS attractive in Spain, thus threatening the achievement of the emissions reduction target. Such findings seem to be robust to the technology to be retrofitted (see Insley [47] for Integrated Gasification Combined Cycle plants and Zhang et al. [32] or Wang and Du [36] for super critical power plants), also when cap-and-trade systems for several pollutants are considered [31] or when the emission reduction target is voluntary [32,36].[9] Furthermore, higher allowance prices seem to be necessary to make coal plant owners fully switch to cleaner technologies (e.g., natural gas in Laurikka [48]; nuclear in Brauneis et al. [49]; biomass in Fuss et al. [50]).[10]

Focusing on RES, several studies indicate that a market-driven development of renewables is still unlikely. Mo et al. [51], as well as Petitet et al. [8] see an increase in the feasibility of wind power investments only under a stable and high CO_2 price. Hieronymi and Schuller [33] also note that allowing abatement via secondary certified emission reductions permits has a negative impact on the investment probability, with consequent need for direct RES subsidies. Although some contributions point out how the introduction of carbon price stabilization mechanisms such as a CO_2 price floor would be beneficial [8,49,51], several capacity expansion studies [39,52,53] confirm the above result by indicating that, absent environmental and/or technology policy instruments, the transition to RES is not profitable for the investor in the short run.

The findings for technology policies are less obvious. On the one hand, the majority of the reviewed literature, even very recent work, indicates that adoption of RES technologies remains unlikely without direct support policies, due to financial unviability under current market conditions as compared to conventional technologies [37,41,54]. For example, looking at onshore wind investments in the Iberian peninsula and in the context of recent policy revisions, Sisodia et al. [55] highlight how the reduction in government generation incentives will lead to delayed investments and, ultimately, challenge the de-carbonization process. Similarly, Schwanitz and Wierling [40] find that investments in offshore wind power are today not yet profitable in Germany, even under a direct support policy like feed-in tariffs. Analogous results seem to hold for solar PV systems. An application to the US Midwest [56] indicates that current policies are unlikely to trigger adoption by a risk-neutral residential consumer unless the federal tax credit is significantly increased.[11] On the other hand, the work by Torani et al. [38] demonstrates that a shift towards solar PV in the residential and commercial sector can occur independently of RES and carbon mitigation policies, which, according to the authors, have a modest role compared to technological change.

A few other studies have recently contributed to the debate on the design and role of technology policies by focusing on the comparison of different policy instruments (e.g., direct subsidies, tradable green certificates) or on the presence of complementary policies.

More in detail, by comparing renewable portfolio standards, feed-in tariffs, and tax credits, Ritzenhofen et al. [26] shift the attention from the ability of such schemes to drive investments, to the evaluation of how they affect sustainability, affordability, and reliability of power systems. The authors find that the three support schemes increase RES penetration, but none is preferable across all criteria. The indication is that RES support schemes need to be assessed in light of market conditions, complementary regulatory schemes, as well as policy objectives.

Another example of a comparative study is the work by Iychettira et al. [29]. Through agent-based modeling, this study shows that the design elements of a RES policy (quantity warranty vs. price warranty, technology specificity vs. neutrality, and *ex-ante* vs. *ex-post* price setting), rather than the policy itself, have significant impacts on welfare and its distribution. The authors' results corroborate the use of competitive bidding to incentivize investments (quantity rather than price warranty) and indicate how the choice between technology specificity vs. neutrality (and, to a lower degree, between *ex-ante* vs. *ex-post* price setting) has significant implications in terms of government spending.[12]

Finally, Boffa et al. [57] theoretically investigate the effect of overlapping environmental and technology policies. This work models the decision to invest in a (generic) RES technology by the owner of a (generic) carbon intensive plant, under market uncertainty and different combinations of carbon mitigation policies and RES subsidies. Interestingly, the study suggests that the incentives provided by the overlap of these two policies strongly depend on the implementation details, which translate into different levels of uncertainty for the investor. For example, in the presence of a price mechanism (e.g., a carbon tax), feed-in tariffs do not seem to stimulate the adoption of RES technologies by a risk neutral investor. In other words, the complementarity of environmental and technology policy is not guaranteed, and the authors highlight the importance of taking into account the environmental policy in place in order to design more effective direct RES support schemes.

In sum, all findings related to environmental policies convey the same message: "a pure permit trading system will not suffice as the sole driver in reaching the target of a de-carbonized economy. A mixture of policy instruments appears instead to be necessary to stabilize our climate" ([49], p. 198). Nevertheless, the analyzed literature seems to question the effectiveness of complementary/overlapping policies, indicating the need for additional, more detailed analysis. Furthermore, recent studies have shifted the focus of the debate away from the mere efficacy of the policy regime in stimulating less-carbon intensive investments and towards its effect on affordability (welfare and its distribution) as well as reliability of supply. These later issues appear relevant not only for developed economies but also for emerging ones. Finally, the little available evidence on more recent RES policy approaches (e.g., competitive bidding) or the role played by non-professional investors leaves room to further empirical and theoretical investigation.

5.2. Policy uncertainty

From a conceptual point of view, policy uncertainty can be defined as the lack of credible commitments by governments and/or regulators [58]. In more empirical terms, it is defined here as uncertainty over either the introduction (or the removal) of a policy, or the change in the design details of an existing one, including the related implementation

[9] However, while in Zhang et al. [32] the result would not change in presence of government subsidies, Wang and Du [36] indicate that a government subsidy might have a significant effect in reducing the critical carbon price for such an investment.

[10] In addition, Wickart and Madlener [79], in studying the adoption of a cogeneration plant vs. boiler only, specify how policy measures (also those which do not directly affect energy price volatility directly, such as a carbon tax) might modify the optimal choice in a non-linear way.

[11] Moreover, in the context of US solar PV, Drury et al. [20] suggest that different policies (R&D spending, system performance guarantees, and long-term purchase contracts) are to be preferred in different jurisdictions.

[12] Interestingly, this is the only work where competitive bidding for RES support is discussed.

timing.

Following this definition, policy uncertainty has been the most studied among the different sources of uncertainty identified in Section 2. Specifically, most articles consider some form of carbon policy uncertainty (17 out of 28, Section 5.2.1), while 11 out of 28 (Section 5.2.2) refer to RES policy uncertainty.

5.2.1. Carbon policy uncertainty

Evidence regarding the effects of carbon policy and its uncertainty mostly derives from studies on the adoption of conventional power plants and retrofitting technologies. In the revised literature, only two contributions focus on renewables [59,60].

The representation of an uncertain carbon policy can considerably vary from one study to another. More precisely, a distinction needs to be made between taxes and quota systems. While uncertainty over a carbon tax might concern its level and implementation or removal timing, the one on quota systems is more complex. Indeed, not only the presence of a market for CO_2 credits naturally determines price fluctuations, but also policymakers might decide to change the price level, the allowance quotas, etc. Nonetheless, given the above definition of policy uncertainty, market price fluctuations, not being determined by policymakers, cannot be labeled as policy uncertainty. For instance, Fuss et al. [50] use the CO_2 price to describe both input price and policy uncertainty. While the volatility of the CO_2 price process (a Geometric Brownian Motion) represents the first one, the probability of future changes in the (initially positive) drift of such a process models the second one. To avoid potential ambiguities, details on how policy uncertainty is modeled are always provided.

As for the effects of policy uncertainty, the surveyed contributions suggest that carbon policy uncertainty has, in general, the predictable effect of delaying the investment in cleaner technologies, unless there are expectations of "unfavorable" regulatory conditions. In a simple setting, Reedman et al. [61] analyze the effect on investments of the introduction of a carbon tax at a future, uncertain date. If the imposition is certain, the investor will invest, and the technology choice will depend on the tax level. However, when both introduction and timing of the tax are uncertain, investments in CCS technologies are delayed. Similarly, Reinelt and Keith [62] employ real options and model policy uncertainty as a carbon tax characterized by uncertain level and implementation date. The study shows that policy uncertainty always deters investments.[13] The idea that investors prefer to wait for government commitment to an environmental policy before deciding to invest in a CCS module is found, in an analogous setting, by Fuss et al. [50] as well as by Patiño-Echeverri et al. [63]. Another study looking at the effect of carbon policies on renewable technology diffusion also finds that, in the Chinese wind power market, the higher the policy uncertainty (modeled as a price shock at a given time), the higher the project risk premium. In this context, CO_2 price caps and floors, ensuring more price stability, could help reduce such premium [59].

Notably, other work shows that certain details of an uncertain policy can curb its delaying effect on investments. Specifically, it is important to distinguish between the introduction of a new policy and a modification of an existing one. Moreover, the frequency of policy changes matters, together with the time between the investment decision and the policy change.

More in detail, by modeling policy changes as probabilistic jumps in the CO_2 price at given dates, Shahnazari et al. [64] find that the effect of policy uncertainty over investment timing depends on whether such an uncertainty regards the implementation of the CO_2 pricing itself or subsequent changes in the existing policy. While in the second case the investment is delayed (unless CO_2 prices are very high), the opposite occurs in the first case.

[13] Nonetheless, the social cost of policy uncertainty depends on the relative competitiveness of the available technologies with the CCS device.

Fuss et al. [65] focus on the frequency of policy modifications by modeling CO_2 prices in two ways: a Geometric Brownian Motion process to account for small fluctuations (e.g., a slight change in the CO_2 tax level) and a jump process to consider more abrupt policy changes.[14] The study finds that less frequent policy changes over the years, even abrupt, better allow the achievement of long-term climate policy goals, as they trigger earlier investments compared to continuous, though small, modifications to the policy in place, perceived as lack of long lasting commitment.[15]

Yang et al. [66] consider, instead, fluctuations in fuel and CO_2 prices. Both uncertainties are modeled as Geometric Brownian Motions, but CO_2 prices are also subject to - policy - shocks at a given time. As for the latter, the interesting result is the negative relationship between the value of waiting before investing and the time between the investment decision and the policy change: the shorter this time, the higher the risk premium. In other words, there is more to lose by investing now if uncertainty will resolve relatively soon.[16]

Adopting a similar approach, Liu et al. [67] find that, with highly volatile CO_2 prices, investments in Combined Cycle Gas Turbines plants (aimed to phase out coal plants) are triggered earlier than under stable prices.

Finally, some very interesting contributions highlight another type of investors' response to policy uncertainty. Specifically, several studies unanimously indicate that uncertainty favors diversification strategies in the technology mix choice [68].

Adopting a real option approach, Fuss et al. [60] demonstrate that it is more likely for wind technologies to enter the optimal investment portfolio when it is not clear which emission target and which socio-economic scenario will occur. In a two-stage stochastic programming model, Hu and Hobbs [17] also find that, if there is uncertainty over the introduction of a CO_2 cap, the optimal stochastic strategy calls for more attention to low-emitting and more efficient technologies.[17] Similarly, Fan et al. [22] define policy uncertainty as the positive probability that there will be climate regulation (cap-and-trade or carbon tax) in a second stage. The results from the two-stage partial equilibrium model suggest that higher uncertainty on CO_2 allowances obtaining generates faster adoption of cleaner technologies, as this enables hedging against environmental policy risk.

As a corollary, Kettunen et al. [24] show that CO_2 price uncertainty promotes higher market concentration, as large incumbents are less risk averse and, therefore, more prone to invest. However, this effect can be alleviated via caps and floors, as well as through early transmission of carbon price shocks. The latter ones could induce investments even by risk-averse market players.

The issue of risk is further explored by Barradale [4]. Based on information from a 2006 survey of 700 individuals working in the power sector, the author introduces a novel definition (or, better, measure) of carbon risk, the "expected carbon payment". This is the product of expected carbon price (that is, the cost of permits/tax in a given scenario times the probability of that policy scenario - or a weighted

[14] While the jump process for CO_2 prices well reflects the definition of policy uncertainty considered in this review, the Geometric Brownian Motion does not, because the fluctuations described might also derive from regular trading in the emissions credit market and not from policymakers' decisions. Nonetheless, in order to respect the main interpretation given by the authors, CO_2 price uncertainty is still classified as an expression of policy uncertainty.

[15] It is worth noting that this result strongly depends on the positive trend assumed for CO_2 prices.

[16] Such a result confirms the one previously found by Blyth et al. [80] in a similar setting analyzing CCS investments.

[17] According to the authors, such an uncertainty is more important than the ones on electricity demand and fuel prices, as also noted by Fuss et al. [50]. On the contrary, Di Lorenzo et al. [18], by assigning a probability distribution to the level of a carbon tax, find that such an uncertainty does not play a significant role in determining net present value, internal rate of return, and payback period of green technology investments (namely, CCS devices), being capital cost and input-fuel price uncertainties more important.

average of multiple scenarios) and expected probability of payment (that is, the probability that the prevailing carbon price will have to be paid in the case of a particular investment), specific to the individual investor and depending on the type of contract and the plant ownership arrangement. The actual effect of policy and policy uncertainty is found to vary across individuals, implicitly suggesting that theoretical representations of investment decisions under policy uncertainty should take this heterogeneity into account.

In sum, from the point of view of its contribution to carbon mitigation in the power sector, environmental policy uncertainty conveys some ambiguity. In fact, although evidence indicates that less frequent, albeit major changes seem to be less detrimental than frequent ones, the selected literature strongly supports policy stability. Nevertheless, an uncertain policy also triggers risk hedging responses, where investors preferably include renewables in the technology mix. Similarly, higher volatility in carbon prices also prompts adoption. Additional implications include avoiding policies that are perceived as not stringent by actors in the power market. This would worsen the detrimental effect of policy uncertainty.

5.2.2. Renewable policy uncertainty

Renewable policy is intended as a technology policy aimed to spur adoption of RES technologies for power generation. Consistently, only generation incentives like feed-in tariffs or renewable portfolio standards (with the related market for green certificates) are considered here, together with investment subsidies, and with the exclusion of R&D subsidies. Also in this context, policy uncertainty might be defined as uncertainty over the introduction timing of a brand-new support scheme (or, symmetrically, the removal of an existing one), as well as over future changes in the details of a support scheme already in place (e.g., subsidy level, period length, etc.). Though the debate on RES policy uncertainty is relatively more recent than the one on carbon policy uncertainty, the literature provides a clear understanding on several issues.

Generally speaking, technology policy uncertainty is of crucial importance to investors. Fleten et al. [69] focus on the role of expectations on future policy implementations and show that investors do take them into account in their technology adoption decisions. The study also confirms that RES policy uncertainty generally acts as a deterrent for new power generation investments. Two other contributions point clearly in this direction. In an empirical analysis on the US electricity sector, Fabrizio [70] builds a proxy for regulatory uncertainty by looking at the history of legislation restructuring and at subsequent repeals, if any. The study finds that the level of new RES investments is lower in states characterized by high regulatory instability. Such an uncertainty emerges as particularly important when investments are highly specific to regulation. Similarly, Nemet [71] codes information on policy existence and stringency to analyze the diffusion of wind power in six different countries and five US states over the period 1980–2008. The main findings are twofold. First, the observed policy volatility has negatively affected the level of investment over time. Second, by comparing several geographies, it can be shown that policy (and market structure) volatility is higher at a single country level than at the world level. As policy changes in different countries/states are uncorrelated, investors are suggested to operate globally for risk hedging.

As in the case of environmental policies, other studies show that certain aspects of an uncertain policy modulate its effect on investments. Here, it is necessary to distinguish between the introduction vs. termination of a (favorable) policy.

A comprehensive contribution in this respect is provided by Chronopoulos and Hagspiel [72]. Specifically, the authors investigate how wind power investments' timing is affected by policy uncertainty, which is modeled through Poisson processes and can take several alternative shapes. In this setting, a subsidy (a fixed proportion on top of the uncertain electricity price) can be permanently retracted and/or suddenly provided. The study clearly shows that, if there is some chance that the subsidy will be retracted (provided) permanently, the investment will be anticipated (postponed), in order to benefit from the support for a longer period.

Other contributions on policy termination confirm these results. Boomsma and Linnerud [73] employ real options to study the effect of the possible termination of a subsidy payment at a random point in time, with expectations over possible retroactivity. The termination is motivated by the technology having reached maturity. While with expectation of no retroactive subsidy termination investments will be anticipated to lock subsidies, the opposite will occur if retroactive effects are forecasted. The contribution by Eryilmaz and Homans [74], focusing on the US wind power sector, analyzes the impact of stochastic state-level certificate prices (designed through a Bernoulli process) and of an uncertain federal production tax credit policy with given electricity prices. The study finds that, intuitively, the (revenue) uncertainty coming from certificate prices is less harmful in terms of investment decision, once a fixed revenue source like production tax credit is introduced. As noted by Boomsma and Linnerud [73], the higher the probability of production tax credit termination, the higher the incentive to invest early in wind power. In other words, investors prefer to act before the policy is terminated, in order to still benefit from it. One the same line, although not strictly on termination, the study by Garnier and Madlener [44] highlights that investments in partially subsidized technologies are more likely to be postponed when subsidies are stable than when they are declining.

Linnerud et al. [28] examine, instead, the reaction of investors to the possible introduction of a green certificates system, when also electricity prices are uncertain. In accord with Chronopoulos and Hagspiel [72], this study finds that utilities and other professional investors tend to delay the investment in face of policy uncertainty (even when the support policy is announced to be retroactive). In addition, as mentioned in Section 4, this study also finds that, in practice, farmers and other non-professional investors do not attach any value to waiting for the uncertainty to resolve.

Boomsma et al. [43] find that the probability of a regime switching (from green certificates to feed-in premium or the other way around) increases the value of waiting before investing. Interestingly, if the switch is envisaged when feed-in premiums are in place, the value of waiting is higher, as the new regime (that is, green certificates) increases risk exposure.

Finally, a few studies focus on the expectation of multiple policy changes over time. This line of inquiry points in the direction of potential boom-bust cycles in RES investments, reduced incentives to invest, or a higher value for modularity.

For example, Barradale [25] analyzes the effect that uncertainty over the periodic renewal of production tax credits has on the timing of wind power investments in the US. Specifically, this study distinguishes between single-party vs. multi-party investment decisions: while the first ones are not influenced by the presence and potential renewal of production tax credits (thanks to a retroactivity clause for eligibility to the support), the latter ones are. Indeed, the combination of highly diffused purchase power agreements (which contain an agreement on future prices) and uncertain policy renewal makes investments more volatile.[18] More than other factors specific to the wind power industry, such volatility generates boom-bust investment cycles which, according to the author, policy stability might help attenuate.

Similarly, Reuter et al. [16] consider a strategic setting in which the firm willing to build new capacity can choose between a polluting (coal) technology and a RES (wind) technology. Based on the example

[18] In other words, as long as the investment is profitable also without production tax credits, policy uncertainty does not represent a concern for single-party investment decisions. Nonetheless, such an uncertainty might be relevant for those investments which would be undertaken in presence of production tax credits, but not otherwise.

of Germany, the authors assume that the feed-in tariff system can end in any period and be reintroduced afterwards. This kind of uncertainty calls for a higher tariff level in order to incentivize investments.

The above-mentioned study by Chronopoulos and Hagspiel [72] also shows that when policy interventions are frequent, the value of stepwise investments is higher as compared to lumpy sum ones. Indeed, wind power projects are characterized by discretion over capacity choice and by the possibility to be developed in stages.

Overall, the literature on technology policy uncertainty provides consistent findings on the detrimental effect of instability on investments in RES technologies. This potentially leads to lower levels of installed capacity, strategic anticipation or deferral of technology adoption, as well as boom-and-bust cycles. Hence, if adoption needs to be stimulated, transparency and less ambiguity regarding regime changes become as critical as the design of the policy itself. Symmetrically, when policy changes are (inevitably) required, a sound regulatory approach to the transition needs to internalize well-known, predictable investors' responses.

Another interesting question is whether the relevance of the policy, hence its stability, might have been overrepresented in the literature, in light of decreasing technology costs, additional revenue opportunities linked to changes in market design, and environmental attitudes of decision makers, influenced for instance by values shared in local communities.[19] In this new scenario, market exposure and policy risk are both present, but technological diversification also becomes more accessible [44]. In other words, studies regarding policy uncertainty should attempt to capture relevant features of the upcoming technology and policy environment, rather than keep focusing on more traditional organizations of power systems. The latter might be more relevant in some jurisdictions than others, but it is certainly relevant in the European context [75].

6. Conclusions

The transition to less carbon-intensive technologies in electricity production is a critical element of the 2 °C scenario set by the Paris Agreement. While market forces are contributing to make relevant technologies increasingly affordable, experience has shown that other factors as well play a role in the decision to invest.

Focusing on the power generation sector, this paper surveys the most recent literature on the subject under the specific conditions that one or more relevant adoption drivers are characterized by uncertainty and that a policy regime is in place. The analysis largely confirms the expected result, that is, the deterring effect of uncertainty over investments. This finding is robust to the methodology adopted (although real option approaches prevail) and extents to all drivers analyzed in the selected contributions, from revenue- and cost- related factors to policy regimes. As for the former ones, less common considerations on aspects that moderate (or, in some cases, revert) the prevailing result also emerge. These aspects include investors' characteristics, like risk aversion, which in some cases generates anticipated, precautionary investments; the planning horizon, which has a positive effect on the probability of an earlier adoption by environmentally concerned investors; and the rate of technological change, as technological maturity is often a crucial determinant of adoption. As for the policy regime, few contributions question the importance of government interventions or the need of stable policy makers' commitment to the energy transition. Indeed, only a few (not necessarily advisable) aspects of policy interventions, like termination or retroactivity, are shown to induce earlier adoption.

Several directions for further research emerge from the present work. As for revenue- and cost- related factors, of particular interest today are questions related to the increasing variety of investors, together with the higher complexity of their interactions. In this respect, the study of potential behavioral biases and/or the assumption of bounded rationality appear extremely relevant to understand future investors' decisions of less traditional actors (e.g., final consumers, aggregators, and energy communities). Furthermore, more effort is required to include the effect of higher uncertainty regarding price signals, which derive from the ongoing integration of renewables and active consumers in wholesale electricity market and their progressive involvement as provider of ancillary services. Notably, this is facilitated by innovations in communication technology (smart meters, smart homes, etc.), whose rate of change is also unpredictable – but not mentioned in the surveyed literature. Similarly, only a few studies deal with the level of investment, and even less with market structure, although such issues will become increasingly important with the growth in RES installed capacity. For instance, the effect of renewables on wholesale electricity prices, often neglected so far, will need to be correctly interpreted. Finally, relevant drivers of green technologies diffusion, such as information transfer, or the role of social norms and investors' environmental attitudes, have yet to be fully addressed in the analyzed context.

Furthermore, additional evidence on the role of emerging policy designs and their effects on welfare and its distribution is certainly needed. For instance, the literature has only recently addressed the issue of overlapping, environmental and technology policies, in particular under uncertainty. Also, thanks to increasing knowledge on the investor's response to policy changes, such as strategic anticipation and deferral in adoption, it would important to understand how decision makers can internalize such conducts when, inevitably, a modification in the policy design becomes necessary. In this sense, individual and collective attitudes towards risk as well as known risk hedging strategies could represent important elements for policy makers' evaluations.

Indeed, the studies included in this survey indicate that, in light of uncertainties of economic/external nature, there is an advantage in investing in a mix of conventional and less-carbon intensive technologies, as well as in resorting to technologies that can be developed in stages (e.g., wind or solar PV, but also storage and active demand in virtual power plant settings). Notably, diversification and modularity are beneficial also in terms of technical/internal uncertainty, as they would help address RES intermittency or uncertain technological change. Furthermore, with particular reference to policy uncertainty, some of the surveyed literature suggests the adoption of strategies of geographical diversification for risk hedging purposes.[20] Nevertheless, little attention has been devoted so far to how uncertainty for investors in green technologies changes across regions. While the issue is sometimes dealt with in more practical risk analyses (see Fraunhofer ISI [82] for an example on RES investments in Europe), the possibility to make regional comparisons would facilitate investors, especially those operating globally. In this respect, in line with Baker et al. [83], the construction of a sector-specific index measuring carbon and RES policy uncertainty across different regions could be extremely useful. Overall, an increased awareness of how the investment environment is evolving in different jurisdictions, together with a better understanding of the behavior of investors is crucial to facilitate the current energy transition and, ultimately, to meet climate targets.

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[19] On this latter issue, see, for instance, Di Lorenzo et al. [81].
[20] We thank an anonymous reviewer for raising these relevant points.

Appendix A

In this Appendix A papers are classified according to the main factors influencing the profitability of a green investment in power generation: *revenue-related factors* (electricity price and demand), variable costs in the form of *input prices* (fuel prices and CO_2 prices), *investment costs*, and *policy regime* (carbon policies and renewable policies). Other *technical factors,* such as technological progress (linked to investment costs) and resource availability (affecting the revenue stream), are also highlighted. Specifically, Table A.1 shows how often the selected contributions deal with a certain factor being uncertain, according to the publication period.

Table A.1
Number of times a factor influencing the profitability of an investment is considered as uncertain in the surveyed articles (2003–2016, biannual data).

Uncertainty Period	**Revenue- related**	**Cost- related**		**Technical factors**	**Policy regime**	**# Articles**
	Electricity price and demand	Input prices (fuel prices and CO_2 prices)	Investment costs			
2003–2004		1				**1**
2005–2006	3	3			1	**3**
2007–2008	6	12		4	4	**11**
2009–2010	1	7	1	1	7	**9**
2011–2012	4	7	2		6	**8**
2013–2014	5	8	3	2	4	**11**
2015–2016*	12	7	4	7	5	**18**
Total	**31**	**45**	**10**	**14**	**28**	**61**

* The period 2015–2016 also includes one article from 2017.

On the cost side, uncertainty on *input prices* (45 articles) has been studied more than uncertainty on *investment costs* (10 articles). One possible explanation is technological: some green technologies, especially less mature ones, have been going through a period of innovations, exposing investors to higher uncertainty on actual investment costs, particularly in more recent years. Another possible – not alternative – explanation is of methodological nature: once investment costs are incurred, they are sunk and no longer uncertain, while variable costs affect profitability in every period, justifying scholars' concerns in case they are uncertain. Such variable costs are often proxied by fuel costs (21 articles) and CO_2 prices (24 articles). As for the latter, they are recognized to have an important role, especially in studies focusing on the comparison between conventional and renewable technologies.

On the revenue side, uncertainty in the *electricity price* appears to be the main source of concern for electricity producers (27 articles), while only few contributions (4 articles) consider uncertainty over *electricity demand* – possibly because of the prevalence of the single power plant perspective.

Technical factors (14 articles)*,* ranging from uncertainty on the availability of natural resources or renewable production to uncertainty on technological progress, are relatively more present only in the last two years, as recent studies tend to combine a larger number of uncertainties in the same model as compared to older ones.

Finally, *policy* uncertainty (28 articles) emerges as extremely important in the process of de-carbonization of power systems, as most green technologies are not yet competitive with conventional ones.

Appendix B

Appendix B provides a brief overview of the range of technologies and countries considered in the survey.

As illustrated in Table B.1, among the studies devoted to the appraisal of the profitability of investing in a particular technology (column *single technology*), a relatively high number of articles deals with *wind* investments (11 articles in the period 2010–2016, one of which on offshore installations). The majority of them considers the European context, while the others analyze the cases of China (2 articles) and the US (2 articles). The second most represented renewable technology is *solar photovoltaics* (6 articles, from 2013 to 2016). Of these contributions, three focus on the residential and commercial sector in the US, two look at the EU and one at China. The more mature *small hydropower* is less represented, with two contributions between 2013 and 2016, both calibrated on the Norwegian case. Finally, the survey includes one 2014 article on the case of *biomass* investments in China, and one article published in 2016 evaluating the investment in a *virtual power plant* (VPP) in Germany.

Moving to studies comparing the profitability of different technologies (column *multiple technologies*), scholars have devoted considerable attention to the transition from CO_2-intensive to CO_2-neutral electricity production, at country level (12 articles). The common characteristic of these generation capacity expansion studies is the inclusion of at least one renewable option. These studies have a large geographical variety (6 look at a

Table B.1
Technologies dealt with in articles published over the period 2003–2016 (biannual data).

Technology Period	**Single Technology**					**Multiple technologies**		**Others****	**# Articles**
	Wind	**Solar PV**	**Small hydro**	**Biomass**	**VPP**	**Including RES**	**Conventional only**		
2003–2004							1		**1**
2005–2006							3		**2**
2007–2008						3	7	1	**11**
2009–2010	3					4	2		**9**
2011–2012	1					3	3	1	**8**
2013–2014	1	2	1	1			4	1	**10**
2015–2016*	6	4	1		1	2	2	3	**19**
Total	**11**	**6**	**2**	**1**	**1**	**12**	**22**	**6**	**61**

* The period 2015–2016 also includes one article from 2017.

** This class mainly includes theoretical contributions and case studies.

European country, 2 at the US and 1 each at Turkey, China, and Japan) and span a nine-year period (from 2007 to 2016). Their shared objective is to determine the technology mix in the power generation sector over the next two to four decades.

Perhaps surprisingly, the highest number of contributions matching the selection criteria of this review is motivated by the impact of climate policy on investments in *coal- and gas-based* generation plants (22 articles in all, only one of which considers only sulphur dioxide emissions). The issue is explored with reference to the European context (11 articles), the US (6 articles), China (3 articles), Australia (2 articles) and at the international level (1 article). For the most part, a coal-based investment is compared with another option: in a few articles, the lower emitting option is a nuclear power plant, in others a gas-fired plant and, in several, retrofitting of the existing power plant with a carbon sequestration technology (or a scrubber) is considered. Notably, the period of highest interest for this subject in the EU is around 2007 and 2008 (6 articles), but lasts until 2014. Similarly, articles regarding the US case mostly appear between 2007 and 2014 (plus one in 2003), while those looking at China are more recent (2013–2016).

Appendix C

Appendix C includes information about the 61 articles selected for the review. For each article, technologies and policies considered, geographical context, methodology, and main result with respect to the relationship between investment timing and uncertainty are specified. This is done by distinguishing between articles assuming certain policy (Table C.1) and those assuming uncertain policy (Table C.2).

Table C.1
Articles dealing with investment in a green technology under uncertain conditions, when policy is certain (34 articles).

Author (year)	Technology	Policy	Country	Methodology	Relationship investment timing/uncertainty
Insley (2003)	Coal retrofitting	Clean Air Act	US	RO	Negative
Laurikka (2006)	IGCC	ETS	EU	RO	negative, no size effect
Laurikka and Koljonen (2006)	coal, gas	ETS	EU	RO	negative, with role for level of CO_2 price
Patiño-Echeverri et al. (2007)	CCS	ETS	US	RO	negative, but mitigated by long planning horizon
Wickart and Madlener (2007)	cogeneration	CO_2 tax	Switzerland	RO	negative, possible nonlinearity
Abadie and Chamorro (2008)	CCS	ETS, investment subsidy	Spain	RO	Negative
Jensen and Meibom (2008)	multiple	ETS	Nordic market	RO	Negative
Kumbaroglu et al. (2008)	multiple	emission restrictions	Turkey	RO	Negative
Szolgayova et al. (2008)	CCS	ETS with price caps	–	RO	negative, with role for level of CO_2 price
Fuss and Szolgayova (2010)	coal, offshore wind	ETS	–	RO	negative, but the magnitude depends on technical change
Zhou et al. (2010)	CCS	ETS	China	RO	Negative
Rentizelas et al. (2012)	multiple	ETS	Greece	linear programming	negative, no RES without policy
Brauneis et al. (2013)	coal, nuclear	ETS with price floors	- (Europe)	RO	Negative
Cristobal et al. (2013)	CCS	ETS	- (Europe)	two-stage stochastic MILP	tradeoff expected profit vs. risk metric
Martinez-Ceseña et al. (2013)	PV	FIT	UK	RO	Negative
Drury et al. (2014)	PV	Retail electricity rates, R&D, Performance Guarantee, Long Term Contract (NPV)	US	Monte Carlo simulations	Negative
Himpler and Madlener (2014)	onshore wind	FIT	Denmark	RO	Negative
Wang et al. (2014)	biomass	subsidy + certified emission reduction	China	RO	Negative
Zhang et al. (2014)	CCS	subsidy + voluntary emission reduction	China	RO	negative, but mitigated by long residual lifetime of the plant
Zhang et al. (2014b)	PV	CDM + FIT	China	RO	Negative
Hieronymi and Schüller (2015)	CCGT, onshore wind	ETS + certified emission reduction	- (Europe)	RO	gas and wind are more cost competitive if long planning horizon
Mo et al. (2015)	CCS	ETS	China	RO	negative, worsened by delays in policy implementation
Boffa et al. (2016)	high-, low-carbon technologies	ETS, carbon tax + FIT, FIP	–	theoretical model	negative, but it depends on the kind of policy
Mo et al. (2016)	onshore wind	ETS	China	RO	negative, with role for level of CO2 price
Petitet et al. (2016)	onshore wind	ETS	- (Europe)	System Dynamics model	negative, with role for level of CO2 price
Ritzenhofen et al. (2016)	multiple	ETS, PTC + RPS, FIT	US	RO	more heterogeneous RES mix if heterogeneous investors
Schwanitz and Wierling (2016)	offshore wind	FIT	Germany	RO	Negative
Sesmero et al. (2016)	PV	home equity loan, federal tax credit, net metering, time-of-day pricing (and combinations)	US	RO	negative, with role for policy support
Sisodia et al. (2016)	onshore wind	FIT, investment subsidies, taxes	Iberian peninsula	RO	negative, worsened by subsidy reduction
Torani et al. (2016)	PV	R&D funds, FITs, consumer subsidies, carbon tax	US	RO	Negative
Wang and Du (2016)	CCS	CDM + subsidy	China	RO	Negative
Welling (2016)	PV	FIT	Germany	RO	ambiguous results of technical uncertainty
Iychettira et al. (2017)	CCGT, RES	FIT, FIP, contract-for-differences	Netherlands	agent based model	need to account for bounded rationality for better policy design

Note. CCGT: Combine Cycle Gas Turbine; CCS: Carbon Capture and Storage; CDM: Clean Development Mechanism; ETS: Emission Trading Scheme; FIP: Feed-In Premium; FIT: Feed-In Tariff; IGCC: Integrated Gasification Combined Cycle; MILP: Mixed Integer Linear Programming; PTC: Production Tax Credit; PV: Photovoltaic; RES: Renewable Energy Source; RO: Real Options; RPS: Renewable Portfolio Standard.

Table C.2
Articles dealing with investment in a green technology under uncertain conditions, when uncertainty is also on policy (28 articles).

Author (year)	Technology	Policy	Country	Methodology	Relationship investment timing/uncertainty
Reedman et al. (2006)	CCS	carbon tax	Australia	RO	Negative
Blyth et al. (2007)	CCS	ETS	- (Europe)	RO	negative, worsened by policy change close in time
Hoffman (2007)	multiple	ETS	Germany	case study	small investors are more sensitive to quota systems
Reinelt and Keith (2007)	CCS	ETS	US	RO	Negative
Fuss et al. (2008)	CCS	ETS	- (Europe)	RO	Negative
Yang et al. (2008)	gas, coal, nuclear	ETS	–	RO	negative, worsened by policy change close in time
Fuss et al. (2009)	CCS, onshore wind	ETS	–	RO	negative, worsened by frequent policy changes
Patiño-Echeverri et al. (2009)	CCS	carbon tax	US	RO	Negative
Barradale (2010)	onshore wind	PTC	US	survey	boom-bust pattern for investments due to policy uncertainty; role of heterogeneous investors
Fan et al. (2010)	coal, gas	ETS, carbon tax	US	two-stage stochastic equilibrium model	positive if risk-averse investor
Hu and Hobbs (2010)	multiple	Clean Air Interstate Rule (caps)	US	two-stage stochastic programming	Negative
Nemet (2010)	onshore wind	FIT, RPS, PTC, etc.	multi-country	econometric model	Negative
Yang et al. (2010)	onshore wind	CDM, certified emission reduction	China	RO	negative, mitigated by CO_2 price caps and floors
Kettunen et al. (2011)	gas, coal, nuclear	ETS with caps and floors	–	RO	negative (even with risk aversion)
Liu et al. (2011)	coal, CCGT	ETS	–	RO	positive if highly volatile CO_2 prices
Boomsma et al. (2012)	onshore wind	FIT, FIP, green certificates	Norway	RO	Negative
Di Lorenzo et al. (2012)	CCS	carbon tax	–	Monte Carlo simulations	negative, but no role for policy uncertainty
Fabrizio et al. (2012)	RES	RPS	US	econometric model	Negative
Fuss et al. (2012)	gas, coal, biomass	ETS	–	RO	negative, but socio-economic scenarios might incentivize wind investment
Reuter et al. (2012)	coal, onshore wind	FIT	Germany	RO	Negative
Barradale (2014)	multiple	ETS, carbon tax	US	survey	negative, but depends on kind of investor
Linnerud et al. (2014)	small hydro	green certificates	Norway	RO	professional and non-professional investors react differently to policy uncertainty
Shahnazari et al. (2014)	coal, CCGT	Clean Energy Act, ETS	Australia	RO	negative, but might be positive if there is uncertainty over policy implementation
Boomsma and Linnerud (2015)	onshore wind	FIT, FIP, green certificates	Nordic region	RO	negative, unless subsidy termination is not retroactive
Chronopoulos et al. (2016)	onshore wind	FIP	–	RO	negative, with policy uncertainty causing lower levels of investment
Eryilmaz and Homans (2016)	onshore wind	RPS, PTC	US	RO	negative, but positive if uncertain subsidy termination
Fleten et al. (2016)	small hydro	green certificates	Norway	RO	negative, with important role of expectations over policy
Garnier and Madlener (2016)	VPP, onshore wind	FIT	Germany	RO	negative, but the effect on the level of investment depends on whether the technology is subsidized or not

Note. CCGT: Combine Cycle Gas Turbine; CCS: Carbon Capture and Storage; CDM: Clean Development Mechanism; ETS: Emission Trading Scheme; FIP: Feed-In Premium; FIT: Feed-In Tariff; PTC: Production Tax Credit; RES: Renewable Energy Source; RO: Real Options; RPS: Renewable Portfolio Standard; VPP: Virtual Power Plant.

References

[1] IPPC. Climate change 2014: mitigation of climate change. Cambridge University Press; 2015.
[2] Bloomberg new energy finance. New energy outlook 2017. 2017.
[3] EU. Proposal for a directive of the european parliament and of the council on common rules for the internal market in electricity 2016; 2016/0380 (COD).
[4] Barradale MJ. Investment under uncertain climate policy: a practitioners' perspective on carbon risk. Energy Policy 2014;**69**:520–35. http://dx.doi.org/10.1016/j.enpol.2014.03.001.
[5] International Energy Agency (IEA). World energy outlook 2016. 2016.
[6] Allan C, Jaffe AB, Sin I. Diffusion of green technology: a survey. Motu Work Pap 2014. [14–04].
[7] Carruth A, Dickerson A, Henley A. What do we know about investment under uncertainty? J Econ Surv 2000;**14**:119–53. http://dx.doi.org/10.1111/1467-6419.00107.
[8] Petitet M, Finon D, Janssen T. Carbon price instead of support schemes: wind power. Energy J 2016;**37**:109–40.
[9] Soroudi A, Amraee T. Decision making under uncertainty in energy systems: state of the art. Renew Sustain Energy Rev 2013;**28**:376–84. http://dx.doi.org/10.1016/j.rser.2013.08.039.
[10] Aien M, Hajebrahimi A, Fotuhi-Firuzabad M. A comprehensive review on uncertainty modeling techniques in power system studies. Renew Sustain Energy Rev 2016;**57**:1077–89. http://dx.doi.org/10.1016/j.rser.2015.12.070.
[11] Fernandes B, Cunha J, Ferreira P. The use of real options approach in energy sector investments. Renew Sustain Energy Rev 2011;**15**:4491–7. http://dx.doi.org/10.1016/j.rser.2011.07.102.
[12] Martínez Ceseña EA, Mutale J, Rivas-Dávalos F. Real options theory applied to electricity generation projects: a review. Renew Sustain Energy Rev 2013;**19**:573–81. http://dx.doi.org/10.1016/j.rser.2012.11.059.
[13] Schachter JA, Mancarella P. A critical review of real options thinking for valuing investment flexibility in Smart Grids and low carbon energy systems. Renew Sustain Energy Rev 2016;**56**:261–71. http://dx.doi.org/10.1016/j.rser.2015.11.071.
[14] Dixit AK, Pindyck RS. Investment under uncertainty. Princeton University Press; 1994.
[15] Abadie LM, Chamorro JM. European CO_2 prices and carbon capture investments. Energy Econ 2008;**30**:2992–3015. http://dx.doi.org/10.1016/j.eneco.2008.03.008.
[16] Reuter WH, Szolgayova J, Fuss S, Obersteiner M. Renewable energy investment: policy and market impacts. Appl Energy 2012;**97**:249–54. http://dx.doi.org/10.1016/j.apenergy.2012.01.021.
[17] Hu M, Hobbs BF. Analysis of multi-pollutant policies for the U.S. power sector under technology and policy uncertainty using MARKAL. Energy 2010;**35**:5430–42. http://dx.doi.org/10.1016/j.energy.2010.07.001.
[18] Di Lorenzo G, Pilidis P, Witton J, Probert D. Monte-Carlo simulation of investment integrity and value for power-plants with carbon-capture. Appl Energy 2012;**98**:467–78. http://dx.doi.org/10.1016/j.apenergy.2012.04.010.
[19] Himpler S, Madlener R. Optimal timing of wind farm repowering: a two-factor real options analysis. J Energy Mark 2014;**7**:3–34. http://dx.doi.org/10.21314/JEM.2014.111.
[20] Drury E, Jenkin T, Jordan D, Margolis R. Photovoltaic investment risk and uncertainty for residential customers. IEEE J Photovolt 2014;**4**(1):278–84. http://dx.doi.org/10.1109/JPHOTOV.2013.2280469.
[21] Abel AB, Dixit AK, Eberly JC, Pindyck RS. Options, the value of capital, and investment. Q J Econ 1996;**111**:753–77.
[22] Fan L, Hobbs BF, Norman CS. Risk aversion and CO_2 regulatory uncertainty in power generation investment: policy and modeling implications. J Environ Econ Manag 2010;**60**:193–208. http://dx.doi.org/10.1016/j.jeem.2010.08.001.
[23] Cristóbal J, Guillén-Gosálbez G, Kraslawski A, Irabien A. Stochastic MILP model for optimal timing of investments in CO_2 capture technologies under uncertainty in prices. Energy 2013;**54**:343–51. http://dx.doi.org/10.1016/j.energy.2013.01.068.
[24] Kettunen J, Bunn DW, Blyth W. Investment propensities under carbon policy uncertainty. Energy J 2011;**32**(1):77–117.
[25] Barradale MJ. Impact of public policy uncertainty on renewable energy investment: wind power and the production tax credit. Energy Policy 2010;**38**:7698–709. http://dx.doi.org/10.1016/j.enpol.2010.08.021.
[26] Ritzenhofen I, Birge JR, Spinler S. The structural impact of renewable portfolio standards and feed-in tariffs on electricity markets. Eur J Oper Res 2016;**255**:224–42. http://dx.doi.org/10.1016/j.ejor.2016.04.061.
[27] Jensen SG, Meibom P. Investments in liberalised power markets. Gas turbine investment opportunities in the Nordic power system. Int J Electr Power Energy Syst 2008;**30**:113–24. http://dx.doi.org/10.1016/j.ijepes.2007.06.029.
[28] Linnerud K, Andersson AM, Fleten SE. Investment timing under uncertain renewable energy policy: an empirical study of small hydropower projects. Energy 2014;**78**:154–64. http://dx.doi.org/10.1016/j.energy.2014.09.081.
[29] Iychettira KK, Hakvoort RA, Linares P, de Jeu R. Towards a comprehensive policy for electricity from renewable energy: designing for social welfare. Appl Energy 2017;**187**:228–42. http://dx.doi.org/10.1016/j.apenergy.2016.11.035.
[30] Klein M, Deissenroth M. When do households invest in solar photovoltaics? An application of prospect theory. Energy Policy 2017;**109**:270–8. http://dx.doi.org/10.1016/j.enpol.2017.06.067.
[31] Patiño-Echeverri D, Morel B, Apt J, Chen C. Should a coal-fired power plant be replaced or retrofitted? Environ Sci Technol 2007;**41**:7980–6. http://dx.doi.org/10.1021/es0711009.
[32] Zhang X, Wang X, Chen J, Xie X, Wang K, Wei Y. A novel modeling based real option approach for CCS investment evaluation under multiple uncertainties. Appl Energy 2014;**113**:1059–67. http://dx.doi.org/10.1016/j.apenergy.2013.08.047.
[33] Hieronymi P, Schuller D. The clean-development mechanism, stochastic permit prices and energy investments. Energy Econ 2015;**47**:25–36. http://dx.doi.org/10.1016/j.eneco.2014.10.008.
[34] Welling A. The paradox effects of uncertainty and flexibility on investment in renewables under governmental support. Eur J Oper Res 2016;**251**:1016–28. http://dx.doi.org/10.1016/j.ejor.2015.12.027.
[35] Zhou W, Zhu B, Fuss S, Szolgayová J, Obersteiner M, Fei W. Uncertainty modeling of CCS investment strategy in China's power sector. Appl Energy 2010;**87**:2392–400. http://dx.doi.org/10.1016/j.apenergy.2010.01.013.
[36] Wang X, Du L. Study on carbon capture and storage (CCS) investment decision-making based on real options for China's coal-fired power plants. J Clean Prod 2016;**112**:4123–31. http://dx.doi.org/10.1016/j.jclepro.2015.07.112.
[37] Wang X, Cai Y, Dai C. Evaluating China's biomass power production investment based on a policy benefit real options model. Energy 2014;**73**:751–61. http://dx.doi.org/10.1016/j.energy.2014.06.080.
[38] Torani K, Rausser G, Zilberman D. Innovation subsidies versus consumer subsidies: a real options analysis of solar energy. Energy Policy 2016;**92**:255–69. http://dx.doi.org/10.1016/j.enpol.2015.07.010.
[39] Fuss S, Szolgayova J. Fuel price and technological uncertainty in a real options model for electricity planning. Appl Energy 2010;**87**:2938–44. http://dx.doi.org/10.1016/j.apenergy.2009.05.020.
[40] Schwanitz VJ, Wierling A. Offshore wind investments - Realism about cost developments is necessary. Energy 2016;**106**:170–81. http://dx.doi.org/10.1016/j.energy.2016.03.046.
[41] Zhang M, Zhou D, Zhou P. A real option model for renewable energy policy evaluation with application to solar PV power generation in China. Renew Sustain Energy Rev 2014;**40**:944–55. http://dx.doi.org/10.1016/j.rser.2014.08.021.
[42] Anadón LD, Baker E, Bosetti V. Integrating uncertainty into public energy research and development decisions. Nature Energy 2017;**2**. http://dx.doi.org/10.1038/nenergy.2017.71.
[43] Boomsma TK, Meade N, Fleten SE. Renewable energy investments under different support schemes: a real options approach. Eur J Oper Res 2012;**220**:225–37. http://dx.doi.org/10.1016/j.ejor.2012.01.017.
[44] Garnier E, Madlener R. The influence of policy regime risks on investments in innovative energy technology. Energy J 2016;**37**:145–60. http://dx.doi.org/10.5547/01956574.37.SI2.egar.
[45] Morales JM, Conejo AJ, Madsen H, Pinson P, Zugno M. Integrating renewables in electricity markets: operational problems. vol. 205. Springer Science & Business Media; 2013.
[46] Insley MC. On the option to invest in pollution control under a regime of tradable emissions allowances. Can J Econ 2003;**36**:860–83. http://dx.doi.org/10.1111/1540-5982.t01-3-00004.
[47] Laurikka H. Option value of gasification technology within an emissions trading scheme. Energy Policy 2006;**34**:3916–28. http://dx.doi.org/10.1016/j.enpol.2005.09.002.
[48] Laurikka H, Koljonen T. Emissions trading and investment decisions in the power sector - A case study in Finland. Energy Policy 2006;**34**:1063–74. http://dx.doi.org/10.1016/j.enpol.2004.09.004.
[49] Brauneis A, Mestel R, Palan S. Inducing low-carbon investment in the electric power industry through a price floor for emissions trading. Energy Policy 2013;**53**:190–204. http://dx.doi.org/10.1016/j.enpol.2012.10.048.
[50] Fuss S, Szolgayova J, Obersteiner M, Gusti M. Investment under market and climate policy uncertainty. Appl Energy 2008;**85**:708–21. http://dx.doi.org/10.1016/j.apenergy.2008.01.005.
[51] Mo JL, Agnolucci P, Jiang MR, Fan Y. The impact of Chinese carbon emission trading scheme (ETS) on low carbon energy (LCE) investment. Energy Policy **89**. 2016. p. 271–83. http://dx.doi.org/10.1016/j.enpol.2015.12.002.
[52] Kumbaroğlu G, Madlener R, Demirel M. A real options evaluation model for the diffusion prospects of new renewable power generation technologies. Energy Econ 2008;**30**:1882–908. http://dx.doi.org/10.1016/j.eneco.2006.10.009.
[53] Rentizelas AA, Tolis AI, Tatsiopoulos IP. Investment planning in electricity production under CO_2 price uncertainty. Int J Prod Econ 2012;**140**:622–9. http://dx.doi.org/10.1016/j.ijpe.2010.11.002.
[54] Martínez Ceseña EA, Azzopardi B, Mutale J. Assessment of domestic photovoltaic systems based on real options theory. Prog Photovolt Res Appl 2013;**21**:250–62. http://dx.doi.org/10.1002/pip.2208.
[55] Sisodia GS, Soares I, Ferreira P. Modeling business risk: the effect of regulatory revision on renewable energy investment - The Iberian case. Renew Energy 2016;**95**:303–13. http://dx.doi.org/10.1016/j.renene.2016.03.076.
[56] Sesmero J, Jung J, Tyner W. The effect of current and prospective policies on photovoltaic system economics: an application to the US Midwest. Energy Policy 2016;**93**:80–95. http://dx.doi.org/10.1016/j.enpol.2016.02.042.
[57] Boffa F, Clò S, D'Amato A. Investment in renewables under uncertainty: fitting a feed-in scheme into ETS. Energy J 2016;**37**:107–22. http://dx.doi.org/10.5547/01956574.37.SI2.fbof.
[58] Brunekreeft G, McDaniel T. Policy uncertainty and supply adequacy in electric power markets. Oxf Rev Econ Policy 2005;**21**:111–27. http://dx.doi.org/10.1093/oxrep/gri006.
[59] Yang M, Serclaes PDT, Buchner B. Wind farm investment risks under uncertain CDM benefit in China. Energy Policy 2010;**38**:1436–47. http://dx.doi.org/10.1016/j.enpol.2009.11.024.
[60] Fuss S, Szolgayová J, Khabarov N, Obersteiner M. Renewables andclimate change mitigation: irreversible energy investment under uncertainty and portfolio effects. Energy Policy 2012;**40**:59–68. http://dx.doi.org/10.1016/j.enpol.2010.06.061.
[61] Reedman L, Graham P, Coombes P. Using a real-options approach to model

technology adoption under carbon price uncertainty: an application to the Australian electricity generation sector. Econ Rec 2006;**82**:S64–73. http://dx.doi.org/10.1111/j.1475-4932.2006.00333.x.

[62] Reinelt PS, Keith DW. Carbon capture retrofits and the cost of regulatory uncertainty. Energy J 2007;**28**:101–27.

[63] Patiño-Echeverri D, Fischbeck P, Kriegler E. Economic and environmental costs of regulatory uncertainty for coal-fired power plants. Environ Sci Technol 2009;**43**:578–84. http://dx.doi.org/10.1021/es800094h.

[64] Shahnazari M, Mchugh A, Maybee B, Whale J. Evaluation of power investment decisions under uncertain carbon policy : a case study for converting coal fired steam turbine to combined cycle gas turbine plants in Australia. Appl Energy 2014;**118**:271–9. http://dx.doi.org/10.1016/j.apenergy.2013.12.050.

[65] Fuss S, Johansson DJA, Szolgayova J, Obersteiner M. Impact of climate policy uncertainty on the adoption of electricity generating technologies. Energy Policy 2009;**37**:733–43. http://dx.doi.org/10.1016/j.enpol.2008.10.022.

[66] Yang M, Blyth W, Bradley R, Bunn D, Clarke C, Wilson T. Evaluating the power investment options with uncertainty in climate policy. Energy Econ 2008;**30**:1933–50. http://dx.doi.org/10.1016/j.eneco.2007.06.004.

[67] Liu G, Wen F, MacGill I. Optimal timing for generation investment with uncertain emission mitigation policy. Eur Trans Electr Power 2011;**21**:1015–27. http://dx.doi.org/10.1002/etep.493.

[68] Hoffmann VH, Federal S, Eth TEU. ETS and investment decisions : the case of the German electricity industry. Eur Manag J 2007;**25**(6):464–74. http://dx.doi.org/10.1016/j.emj.2007.07.008.

[69] Fleten S-E, Linnerud K, Molnár P, Tandberg Nygaard M. Green electricity investment timing in practice: real options or net present value? Energy 2016;**116**:498–506. http://dx.doi.org/10.1016/j.energy.2016.09.114.

[70] Fabrizio KR. The effect of regulatory uncertainty on investment : evidence from renewable energy generation. J Law, Econ Organ 2013;**29**(4):765–98. http://dx.doi.org/10.1093/jleo/ews007.

[71] Nemet GF. Robust incentives and the design of a climate change governance regime. Energy Policy 2010;**38**:7216–25. http://dx.doi.org/10.1016/j.enpol.2010.07.052.

[72] Chronopoulos M, Hagspiel V, S-EF.. Stepwise green investment under policy uncertainty. Energy J 2016;**37**:87–108.

[73] Boomsma TK, Linnerud K. Market and policy risk under different renewable electricity support schemes. Energy 2015;**89**:435–48. http://dx.doi.org/10.1016/j.energy.2015.05.114.

[74] Eryilmaz D, Homans FR. How does uncertainty in renewable energy policy affect decisions to invest in wind energy? Electr J 2015;**29**:64–71. http://dx.doi.org/10.1016/j.tej.2015.12.002.

[75] Voss A, Madlener R. Auction schemes, bidding strategies and the cost-optimal level of promoting renewable electricity in Germany. Energy J 2017;**38**. http://dx.doi.org/10.5547/01956574.38.SI1.avos.

[76] Gardner DT, Rogers JS. Planning electric power systems under demand uncertainty with different technology lead times. Manag Sci 1999;**45**:1289–306. http://dx.doi.org/10.1287/mnsc.45.10.1289.

[77] Keppo J, Lu H. Real options and a large producer: the case of electricity markets. Energy Econ 2003;**25**:459–72. http://dx.doi.org/10.1016/S0140-9883(03)00048-3.

[78] Jouvet PA, Le Cadre E, Orset C. Irreversible investment, uncertainty, and ambiguity: the case of bioenergy sector. Energy Econ 2012;**34**:45–53. http://dx.doi.org/10.1016/j.eneco.2011.08.018.

[79] Wickart M, Madlener R. Optimal technology choice and investment timing: a stochastic model of industrial cogeneration vs. heat-only production. Energy Econ 2007;**29**:934–52. http://dx.doi.org/10.1016/j.eneco.2006.12.003.

[80] Blyth W, Bradley R, Bunn D, Clarke C, Wilson T, Yang M. Investment risks under uncertainclimate change policy. Energy Policy 2007;3**5**:5766–73. http://dx.doi.org/10.1016/j.enpol.2007.05.030.

[81] Koirala BP, Koliou E, Friege J, Hakvoort RA, Herder PM. Energetic communities for community energy: a review of key issues and trends shaping integrated community energy systems. Renew Sustain Energy Rev 2016;**56**:722–44. http://dx.doi.org/10.1016/j.rser.2015.11.080.

[82] Fraunhofer ISI. The impact of risks in renewable energy investments and the role of smart policies. Final report for EU DiaCore project, February 2016.

[83] Baker SR, Bloom N, Davis SJ. Measuring economic policy uncertainty. Q J Econ 2016;**131**(4):1593–636. http://dx.doi.org/10.1093/qje/qjw024.